R+D 8280-AN-01

COMBUSTION OSCILLATIONS, EXTINCTION AND CONTROL

Final Technical Report

by

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May 1998

United States Army

EUROPEAN RESEARCH OFFICE OF THE U.S. ARMY

London, England

CONTRACT NUMBER N68171-97-C-9035

Imperial College of Science, Technology & Medicine

ICON Ltd

SUMMARY OF RESEARCH

The contract was signed on 7 June 1997 and began officially on that date although considerable preparations had been made. As stated in the Proposal, it was undertaken mainly by one post-doctoral research assistant, Dr K Sardi, working with the Principal Investigator with contributions from Drs S Sivasegaram and A M K P Taylor and my Messres S R N De Zilwa and R Bhidayasiri. Five interim reports have been provided together with six technical reports and two additional technical reports which contribute to a second contract.

The objectives of the research were to determine the extent to which discrete frequency oscillations affect extinction of interacting flames, including those formed by lean mixtures of gas and air, and to assess a possible method to represent this effect by a theoretical model of extinction. This objective was carried out in accord with the plan described in Appendix A and taken from the proposal. It required the design and commissioning of two experimental facilities and the development and evaluation of a new method for the representation of oscillating flames and their extinction and possible re-light. The two facilities corresponded to a model of the combustor of a land-based gas-turbine able to operate with premixed fuel and air over a range of equivalence ratios with emphasis on lean values, and to opposed flames which were also based mainly on premixed gaseous fuel and air with emphasis on lean mixtures. The first provided results with parallel annular and stabilising core flows and the second gave rise to a near one-dimensional flow which allowed close examination of the effects of strain, including strain due to oscillations, on extinction.

Naturally occurring pressure oscillations in the model combustor were quantified with heat release around 100 kW as a function of geometric and flow parameters and actively controlled by the oscillation of fuel flow, references 1, 7 and 9. Flame stabilisation was behind an annular ring and a step with higher equivalence ratios in the core flow. Amplitudes up to 10 kPa were dominated by the quarter-wave frequency of the duct length upstream of the annular ring, depended on the equivalence ratio of the annular flow and decreased as the annular ring and the step were moved closer. Active control of pressure oscillations was sensitive to the location of addition of oscillated fuel and was more effective with oscillation of fuel in the main flow. Amelioration of pressure oscillations by active control resulted in increase in NOx emissions by between 5 and 15 %.

The experiments with the opposed flames, references 3, 6 and 10, showed that forced flame extinction depended on the total duration of pulsation and ranged from a few milliseconds to almost a second, with amplitude and the frequency of the oscillation as important parameters. Thus extinction times increased quasi-exponentially with decreasing amplitude and increasing frequency of oscillation for diffusion flames but were a non-monotonic function of frequency in premixed flames, with the longest extinction time corresponding to higher frequencies as the flame tended to stoichiometric. The method by which the characteristics of the opposed flames were represented is based on the concept of a mixinglet which expressed the scalar quantities within the interface between the opposed jets in terms of an error function. Its development benefited from early work with isothermal flows, reference 2, and it is described first without imposed oscillations in reference 4 and with imposed oscillations in reference 5. The width of the mixing layer is a function of the sum of the bulk, the turbulent and the periodic strain and the mixinglet is assumed be randomly convected between the opposed jets. The results reproduced measured trends in the mean and rms of the scalar fluctuations and the dissipation in non-combusting, periodically forced, opposed jet flows and include extinction times in opposed flames that increase exponentially with frequency and decreasing amplitude, again in accord with experiment. The method has been designed for inclusion in reduced forms of the Navier Stokes equations and offers considerable promise for the representation of the parallel and opposed flows.

The cumulative probability of the scalar dissipation exceeding a critical quenching value has been shown to be a near-step function of time and this suggests a competitive mechanism between partial quenching of the reaction and re-ignition, so that the it is possible to have alternating near-extinction and re-light in all flames with equivalence ratios near the lean flammability limit. At the same time, the experiments of reference 1 suggested that extinction was associated with periodicity at very low frequencies and this was confirmed by the observations of reference 8 so that the acoustic coupling may be less important.

The objectives of this short contract have been more than fulfilled and remaining tasks include;

* Further examination of the nature of extinction of lean flames stabilised on bluff bodies.

* A parallel examination in opposed flames with oscillations imposed at frequencies from 2 to 10 Hz.

* Modification of the mixinglet model to include variable-density effects and incorporation in a computer code for the solution of unsteady, two- and three-dimensional equations with boundary conditions appropriate to the experiments.

CONDUCT OF TASKS SPECIFIED IN THE PROPOSAL

This section reviews the research in terms of the ten tasks of Appendix A and in number order. The tasks are identified and a summary of the findings reported in each case. More detail is available in the reports referenced and made available with the interim reports. All tasks have been successfully addressed and the following section addresses the new questions which arise from the research.

1. FLOW ARRANGEMENTS

Two combusting flow arrangements were designed, constructed and commissioned with major assistance from a technician and following from the previous work of Bhidayasari (9) and Sardi (10). One was similar to that of the combustors of land-based gas turbines and the other opposed jets with flows of either inert gases or air and combustible gas in combinations from premixed to diffusion. They are shown in figure 1.

2. ACOUSTIC CHARACTERISTICS OF THE MODEL GAS TURBINE

The acoustic characteristics of the model gas-turbine combustor were determined with premixed fuel and air with equivalence ratios from close to the lean flammability limit to values in excess of stoichiometry and with a range of ratios of the velocity in the core and annulus flows, particularly with lean mixtures in the annulus and near-stoichiometric mixtures in the core flow and as a function of the distance separating the annular ring and step on the wall, thermal load, air-fuel ratio of the main flow and the proportion of flow in the central pilot flame.

The results show that equivalence ratios of 0.7 or more in the annulus led to rough combustion, and tests with upstream duct lengths between 5.5 and 12 D confirmed that, with flame stabilisation behind the annular ring as well as the step as intended, oscillations were dominated by the quarter-wave frequency of the duct upstream of the flame-holder. The influence of the equivalence ratio of the pilot stream on the amplitude of oscillations was small, figure 2, except for values around 0.62 at which the amplitude increased as the lean limit was approached, causing the flame to detach from the annular ring and stabilise on the step. This increase was associated with poor stabilisation at the inner edge of the ring and possibly also with a tendency for the flame to extinguish and re-light with low-frequency periodicity.

Combustion oscillations also caused the flame to detach from the annular ring with the area blockage ratio of 0.21 and stabilise entirely behind the step at an equivalence ratio around 0.7 in the main flow. This occurred at values of equivalence ratio close to 0.9 for the larger area blockage ratios of 0.25 and 0.29 but not for the largest value of 0.36. Stabilisation on the step alone gave rise to antinodal rms pressure fluctuations around 2 kPa, compared with more than 5 kPa with the flame attached to the annular ring, and associated with a three-quarter-wave in the entire duct length. An amplitude of 4 kPa was excited, however, with stabilisation behind the step, when the half-wave frequency of the length of the duct upstream of the step matched the quarter-wave frequency of that downstream.

The oscillations were ameliorated by a combination of a sensor, feed-back control and actuators which modulated the fuel and air at the frequencies of the natural oscillations. Control of the 125 Hz dominant quarter wave in the upstream duct was achieved by the oscillation of fuel flow in the pilot stream at a frequency of 85 Hz, a quarter-wave in the entire duct, and led to attenuation of the antinodal rms pressure from around 4 to 3.2 kPa. This reduction was comparatively small and detailed investigations were carried out with feedback control and oscillation of fuel flow at the dominant frequency and with a difference in phase.

Preliminary experiments showed that it was necessary to oscillate 7 % of the total fuel flow to achieve useful attenuation and that the result was insensitive to phase within 30 degrees of the optimum. Control performance was sensitive to the mean equivalence ratio in the pilot stream, and figure 3 shows that the attenuation was a maximum when the equivalence ratio in the pilot stream was close to unity; it also shows that the antinodal rms of pressure fluctuations could be attenuated by around 12 dB at an equivalence ratio of 0.7 in the annular duct, but the attenuation declined with increase in overall equivalence ratio and was negligible for values greater than 0.75. It is evident that attenuation was poor at an equivalence ratio of around 0.65 and, in general, it appears that attenuation of small amplitudes of oscillation requires a more sensitive control system. The difficulty in controlling oscillations at equivalence ratios greater than 0.75 was due to the oscillated fuel not being available at the location where it was most effective.

Pressure oscillations in the annular flow were associated with the ring and their amplitude was more sensitive to fuel concentration in the annulus than at the core flow, mainly because the most intense part of the heat release was associated with the flame developing from the outer edge of the ring. Active control was implemented by the oscillation of fuel in the annulus with the three injectors and cross-jets of air to deliver the oscillated fuel close to the outer edge of the annular ring. The oscillated injection of approximately 3.5 % of total fuel into the main flow led to the amelioration of pressure fluctuations by around 6 dB for the range of equivalence ratios examined, compared with the oscillation of up to 10 % in the pilot stream and ineffective control with equivalence ratios greater than 0.75.

In general, the emissions of NOx increased with decreasing amplitude of oscillations with differences up to around 15% and consistent with previous findings.

3. MEASUREMENTS OF EXTINCTION IN OPPOSED FLOWS

The influence of the mean and instantaneous strain rates on extinction of combinations of lean premixed and diffusion flames was determined in the opposed flows. The extinction velocities and bulk strain rates of partially premixed flames with air volume fractions in the fuel stream of 0.5 and 0.8 respectively were 15% and 25% greater than with diffusion flames as shown in figure 4a, and increased further with single premixed flames stabilised against air, with the maximum extinction strain rate at an equivalence ratio of unity and 80% higher than that of the partially premixed flames, figure 4b. When the opposed stream was replaced by fuel, there was a further increase of the extinction limits so that it was possible to stabilise very lean flames, suggesting diffusion of excess air from the lean mixtures or fuel from the opposed stream and that the lean flames burned with overall higher equivalence ratios. Thus, the extinction velocity of single premixed flames stabilised against a fuel stream achieved a maximum at an equivalence ratio of 0.9 instead of unity. It is anticipated that diffusion of air and reactants also occurred with the single premixed flames stabilised against an air stream, leading to partial dilution of the reactants, so that these flames burned with overall lower equivalence ratios and with lower extinction limits than the premixed flames stabilised against a fuel stream. Twin lean premixed flames with the same equivalence ratio in the two streams, referred to here as *symmetric*, extinguished at strain rates approximately twice those of single lean flames due to the high-temperature combustion products in the intervening region. Also opposed flames of unequal equivalence ratios, referred as *asymmetric*, extinguished at higher strain rates than twin symmetric flames due to the diffusion of the excess fuel from the rich to the lean mixture resulting in an overall equivalence ratios which tended to stoichiometric. Thus, the rich flammability limit of twin symmetric flames was the same as for single premixed flames against fuel and 20 % lower than for single flames against air, consistent with diffusion of air from the opposed stream to the flammable mixture in the single premixed flames.

Additional experiments with lean mixtures of equal equivalence ratios in the range 0.5 to 0.7 in one flow and the other with an equivalence ratio of 0.9 revealed that extinction strain rates were greater for asymmetric flames with the same total quantity of fuel and *total* equivalence ratios less than 0.7, based on the fuel and air mixtures of both streams. For example, asymmetric flames of 0.6 total equivalence ratio extinguished at bulk strain rates 70% higher than those of symmetric flames, figure 5.

4. MEASUREMENTS IN OPPOSED FLOWS WITH IMPOSED FREQUENCIES

The experiments were extended to include the influence of velocity fluctuations imposed at particular frequencies as a function of amplitude. Diffusion, partially premixed, single premixed flames stabilised against an air or a fuel stream and twin symmetric and asymmetric premixed flames were considered.

The velocity fluctuations imposed by the oscillation were measured with a one-component forward-scatter laser-Doppler velocimeter to provide estimates of the magnitude of the oscillating strain rate. It was found that the rms of the velocity fluctuations due to the oscillations could be up to an order of magnitude larger than that of the turbulence fluctuations in the unforced flow at the exit of the two nozzles, and decreased linearly with distance to about half the initial value at the stagnation plane. Hence the evolution of the velocity fluctuations was due mainly to the *deterministic* fluctuations imposed by the forcing and this is consistent with the measured bimodal velocity probability distributions, figure 6. It was estimated, see reference 3, that the resulting instantaneous periodic strain rate ranged from 35% to 100% of the mean value implying that periodically oscillated flames withstood, for a limited period of time, *instantaneous* strain rates larger than the unforced extinction limits.

Thus, the extinction of periodically forced flames depended on the *duration* over which the oscillation was imposed and may be attributed to gradual cooling of the reaction zone as a result of quenching during the part associated with high strain and re-ignition during that part of the oscillation cycle associated with low strain rate. Extinction times ranged from a few milliseconds to almost a second, increased quasi-exponentially with decreasing amplitude and increasing frequency of oscillation for non-premixed flames, figure 7, but were a non-monotonic function of frequency for premixed flame, with the longest extinction time corresponding to higher frequencies as the flame tended to stoichiometric, figure 8. Premixing of the fuel of the air stream improved flame stability and extinction times reached their maximum for twin stoichiometric flames and decreased as mixtures became leaner or richer. Symmetric lean flames of equivalence ratio less than 0.7 had shorter extinction time scales and were more sensitive to changes in the equivalence ratio than asymmetric flames of the same total quantity of fuel. For example a decrease by 20% in the total equivalence ratio required a decrease in the rms of the imposed fluctuations by a factor of almost two in symmetric flames and by only 20% in asymmetric flames for extinction to occur within five oscillation periods.

5. SCALAR DISSIPATION AS A FUNCTION OF FREQUENCY AND AMPLITUDE

Simultaneous measurements of a passive scalar, temperature, and the axial and radial components of its dissipation were obtained along the centreline of an inert counterflow, with one jet slightly heated and using pairs of parallel cold wires of 0.5 micron in diameter. Bulk strain rate and frequency and amplitude of the imposed periodic strain were varied and results were reported in terms of a normalised variable that has the properties of a fuel mixture fraction so that results can be related to combusting flows.

It was found that the scalar and the axial and radial dissipation components varied sinusoidally with time with fluctuations that increased with amplitude and decreased with frequency of the oscillation. For one half of the oscillation period, phase averaged dissipation values were larger than the respective unforced means so that flame extinction is promoted during this part of the cycle. For the other half of the oscillation period the scalar dissipation was less than the unforced values confirming that reaction is likely to resume and suggesting the presence of a competitive mechanism between local quenching and re-ignition in oscillating flows.

Additional time-averaged measurements of the scalar and its dissipation revealed that low frequency - high amplitude oscillations also affected mixing processes in the mean flow. Figure 9 shows that, for a frequency of 200 Hz. the mean and rms profiles of the scalar and the dissipation do not coincide with their respective unforced values and that mean thickness of the mixing layer increases with amplitude. With higher frequencies, the effects of the imposed oscillation on the evolution of the scalar field became less pronounced and this is consistent with the measurements in the combusting flow that showed that extinction times tend to increases with frequency.

6. CALCULATION METHOD

A calculation method was developed for inert turbulent counterflows, with and without imposed fluctuations. The stochastic model described the correlation between scalar fluctuations and their dissipation and estimated the distribution of the conditional scalar dissipation in flows characterised by 'young' scalar turbulence in the sense that the residence times are smaller than the eddy turn over time. The scalar field was determined from an ensemble of instantaneous scalar interfaces of specified functional form randomly displaced in space and referred to as mixinglets and the results compared favourably with measurements and direct numerical simulations of scalar fields characterised by short residence times.

The model was first formulated to account for molecular diffusion and turbulent convection and its ability to describe conditional scalar moments with application to combustion modelling was addressed. Comparison of calculated and measured single and joint scalar - scalar dissipation statistics revealed that the model can identify the correlation of the scalar fluctuations and their dissipation and describe the distribution of the mean conditional dissipation.

Sensitivity analysis showed that the effect of turbulent convection represented by the random displacements of the scalar interface, dominated molecular diffusion represented by the interface width, in the evolution of the mean unconditional and conditional scalar and dissipation and that the model reproduced experimental trends that relate increase in the bulk strain rate to a subsequent increase in the mean dissipation. However, the instantaneous values of the scalar dissipation, which can be responsible for flame extinction, are also related to the values of the *instantaneous* strain rate. The model was extended to account for the instantaneous turbulent strain rate and the concept of a library of mixinglets was introduced, and characterised by a probability distribution of instantaneous widths. Figure 10 shows the probability distributions of the total strain acting on a scalar interface and the resulting pdf of the instantaneous thickness of the mixing layer. Consideration of the bulk and turbulent straining led clearly to higher values of the instantaneous strain and to smaller values of the mixing layer width, since strain rate and interface thickness are inversely proportional. The instantaneous turbulent strain rate was assumed to have a Gaussian distribution and was related to the width of the instantaneous scalar interface by a time-dependent ordinary differential equation so that transient effects, such as flame-vortex straining, were incorporated. Comparison with measurements revealed that the model of a library of mixinglets was able to represent the rms of the conditional dissipation, the joint probability of the scalar fluctuations and the scalar dissipation irrespective of the value of the stoichiometric fuel mixture fraction, figure 11.

7. CALCULATED STABILITY LIMITS

The concept of the mixinglet was extended to describe a turbulent scalar field under periodic variation in the strain rate and used to show that fluctuations in the width of an instantaneous forced mixing layer, the scalar concentration and the scalar dissipation increase with bulk strain and oscillation amplitude and decrease with frequency.

At low frequencies, the time response of the mixing layer was asymmetric and the asymmetry increased with bulk strain and amplitude, suggesting that periodic forcing is likely to affect mixing processes in the mean flow. Accordingly, the model reproduced measured trends of an increase in the rms of the scalar fluctuations, an increase in the rms of the scalar dissipation and a decrease in the mean dissipation along the centreline between forced opposed turbulent jets for oscillation amplitudes of the order of the bulk strain rate.

The rms conditional dissipation in the forced flow, normalised with its quasi-steady value, scaled with the square root of a diffusion to an oscillation time scale; the former equal to the inverse of twice the bulk strain and the latter equal to the inverse of the angular frequency. This scaling was independent of the bulk strain rate and the amplitude of the oscillating strain so that the ratio of the two timescales can provide an estimate of the response of a mixing layer, and by extension a diffusion flame, to periodic forcing. It was shown that attenuation of the amplitude of the imposed forcing begins at values of the squared time scale ratio of about 0.1 with a final cut-off at values larger than 10, figure 12.

For values of the time-scale ratio below 10 a new extinction criterion was proposed to include the effects of the duration of the oscillation to flame extinction and the results show that the calculated extinction times increase exponentially with decreasing amplitude and increasing frequency in analogy with measurements, figure 13. The calculated cumulative probability of the scalar dissipation exceeding a critical quenching value was shown to be a near-step function of time so that a competitive mechanism exists between the time intervals where the scalar dissipation exceeds the critical value, leading to partial quenching of the reaction, and the times were the scalar dissipation is lower than the quenching limit resulting in re-ignition, figure 14.

8. GAS-TURBINE COMBUSTOR

Additional experiments were performed in the model combustor of task 2 and with the fuel supply as the actuator. The results were similar to those of task 2 for the annular arrangements and were extended to a swirl stabilised flow with premixed fuel and air entering the combustion chamber through tangential and radial entrance slots and a controlling jet of fuel and air axially on the centre line of the upstream end.

This swirled flow also gave rise to rms pressure oscillations up to 10 kPa, which increased with overall equivalence ratio, swirl number and unpremixedness associated with larger fuel concentrations at the centre of the duct. Control reduced the pressure oscillations, associated with a longitudinal mode of the geometrical arrangement, by some 10 dB for values of overall equivalence ratio up to 0.75 above which the flame moved downstream so that the effectiveness of the actuator declined. Control was also attempted with fuel added to one of the tangential entries but was less effective. It was evident that the location of the oscillating jet of fuel and air used for control purposes was important so that when the region of flame stabilisation moved downstream, the controlling jet was not in the correct location to ameliorate the natural oscillation. The oscillation of flow in the tangential and radial entrances was ineffective because the swirling flow in the chamber tended to reduce the amplitude of the controlling oscillation.

9. LINKS BETWEEN OPPOSED FLAMES AND COMBUSTORS

The presence of oscillations in the model combustor, either imposed or naturally occurring, tended to cause extinction when the equivalence ratio was close to the lean flammability limit but the frequency of the acoustic wave was replaced by a much lower value in the latter case. The frequency was in a range up to 10Hz and neither this value nor the amplitude was constant so that control was difficult to implement and more so when the position of flame stabilisation moved, as in the swirl combustor. Imposed oscillations were able to cause extinction for all equivalence ratios in the opposed flames but the number of oscillation cycles required to extinguish the flame decreased with equivalence ratio towards the lean flammability limit, and with the amplitude and frequency of oscillation although the last effect was not monotonic. The mixinglet theory led to results generally in agreement with the extinction results of the opposed flames and both make clear that there is a greater tendency to extinction during one part of the oscillation cycle and a tendency for reduced strain and possible re-light in another. These phenomena are also consistent with the results in the model combustor though much remains to be done to formalise and quantify the link.

10. INFORMATION

The results of the investigation have been submitted for peer review by learned journals as indicated in the list of references and a formal presentation will be made to the 29th AIAA Fluid Dynamics Conference. They have also been communicated formally to the Contract Monitor, Dr R Reichenbach of the US ARMY and to the Director of the NASA, Ames Research Center, and are available on computer disk on request.

REMAINING QUESTIONS AND SOLUTIONS

Much has been learned from the experiments and analysis of the contract research and all promised tasks have been undertaken and with results of major interest. The findings also indicate the need for further research and remaining tasks include those considered in the following paragraphs.

The opposed-flame configuration has provided quantitative evidence of the effect of imposed oscillations in the process of extinction. The investigations encompassed a wide range of frequencies with emphasis on those which might be associated with acoustic characteristics of combustors. Thus, the investigations encompassed a range from around 200 to 1000 Hz rather than the lower values observed in the combustors in the latter stages of this investigation. One remaining tasks is, therefore, to extend the experimental investigation in opposed flame to include imposed oscillations at low frequencies, a range of amplitudes and with modulations of both so that the near-extinction properties of the combustor flows are properly simulated.

It is desirable to quantify the influence of the initial profile in the opposed flows so as to ensure that the results provide meaningful absolute numbers associated with extinction rather than quantitative trends. In the same context, it is evident that profile shapes can be arranged with local and high regions of strain and that these can give rise to local extinction and re-light and further evidence of the nature of local strain can be determined by varying the shape of the mean profiles in the exit planes of the two pipes which form the opposed jets.

A parallel investigation is required to examine the nature of extinction of lean flames stabilised on bluff bodies, to include backward facing steps and annular rings such as those of dump and lean-burn combustor. The late observation of the present contract showed that the flame can extinguish as it traverses circumferential around the region of stabilisation and further information is required to determine the cause and its link with the low frequency oscillations and repeated re-light. This will be achieved by a combination of visual and photographic observations using CCD cameras and also by local measurements, mainly of temperature and with a combination of small-diameter, digitally compensated thermocouples and Rayleigh scattering as proves necessary.

Attempts will be made to control these low-frequency oscillations actively first by pressure oscillations generated by a loudspeaker and then by oscillations of a small proportion of fuel. It is likely that the sensor and controller associated with this task will be more sophisticated than those previously used with acoustic oscillations with ability to determine the appropriate location for fuel oscillation and recognition of frequency modulations in real time. In the case of fuel oscillation, flexibility will be introduced by variation of the quantity oscillated and attempts will be made to automate this process.

The mixinglet model will be extended to include variable density effects as in diffusion and premixed flames and incorporated in a computer code for the solution of unsteady, two-and three-dimensional equations with boundary conditions appropriate to the experiments. It will be used to represent the experiments so far performed and improved as found necessary and also to examine low-frequency oscillations and the consequences of local near extinction and re-light. This part of the work will be performed in conjunction with the opposed flame experiments and with chemie-luminescence and schlieren examination of time-dependent quantities which affect local, time-resolved strain including the nature of the vortex flow from the two pipes.

ACKNOWLEDGEMENTS

This research was conducted with financial support from the US Army and the Principal Investigator is glad to to have this opportunity to express his thanks to the Armand to Drs R Reichenbach and H McDonald of the US Army and the NASA, Ames Research Center respectively for their encouragement and helpful discussions.

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APPENDIX 1; PLAN OF WORK

1. Design, construct and commission experimental facilities, one comprising a flow configuration similar to that of the combustors of gas turbines and the other opposed jets, with the possibility of inert flows and of combustion of premixed reactants of gaseous fuel.

2. Measure the acoustic characteristics of the gas-turbine combustor as a function of the thermal load, air-fuel ratio of the main flow and of the proportion of flow in the central pilot flame. The effect of preheat will be determined also in terms of pressure fluctuations, exit-plane temperatures and emissions of major and minor species. The oscillations will be ameliorated by a combination of a sensor, feed-back control and actuators which will modulate the fuel and air, at the frequency or frequencies of the natural oscillations or at lower harmonics as required, and the measurements repeated to quantify the effects in terms of pressures, temperatures and emissions. Extinction characteristics will be examined as the mean air-fuel ratio approaches the lean limit.

3. Conduct experiments in the opposed flow geometry to determine the influence of the mean and instantaneous strain rates on extinction of combinations of lean premixed and diffusion flames, without and with preheat. The emphasis will be on the determination of the combinations which provide greatest stability under increasing mean and fluctuating strain.

4. Extend the experiments of task 3 to include the influence of velocity fluctuations imposed at particular frequencies as a function of the amplitude of the oscillation, to be quantified at the exit of the counterflow jets using a combination of hot-wire anemometry and laser Doppler velocimetry. The single frequency oscillations will be created by a loudspeaker and by modification of the fuel flow. Consideration will also be given to the presence of two coexisting discrete frequencies. It is expected that the times to extinction will vary from those of a few oscillation cycles to many cycles and emphasis will be given to those that require the shorter times.

5. Measure P(c|xst) using cold wires, particularly as a function of frequency and imposed amplitude and provide phase-averaged values.

6. Develop the calculation method for inert turbulent counterflow, with and without imposed fluctuations, using axisymmetric forms of the equations of motion and scalar transport. The resulting turbulent length scales will allow the prediction of P(c|xst) using a Gaussian assumption for the pdf of the location of the centre of the assumed instantaneous scalar profile.

7. Calculate the stability limits of the non-premixed flame as a function of imposed fluctuation and strain rate, from the inert flow predictions of P(c|xst) of 6, determine cq from a laminar-flamelet program (Rogg) and apply percolation theory to predict extinction. Compare with measurement and extend the calculation procedure to premixed flames and then to combinations of premixed and non-premixed flames.

8. The gas-turbine combustor of 2 will be operated with discrete-frequency oscillations applied as in the opposed jets but with the fuel supply as the actuator. The extinction characteristics will be examined for a range of parameters similar to those for the opposed jets, and the same emission measurements will be recorded.

9. Attempts will be made to link the results of the two geometrical arrangements and with the theory.

10. Assemble the information gained from the above tasks in a form convenient for use in industry so as to assist directly in the reduction of problems associated with unstable combustion of lean air-fuel mixtures; and provide a considered statement of geometries and control mechanisms which should be investigated in greater depth, together with a detailed experimental plan, to help the gas turbine industry to achieve low emissions of oxides of nitrogen with acceptable stability.

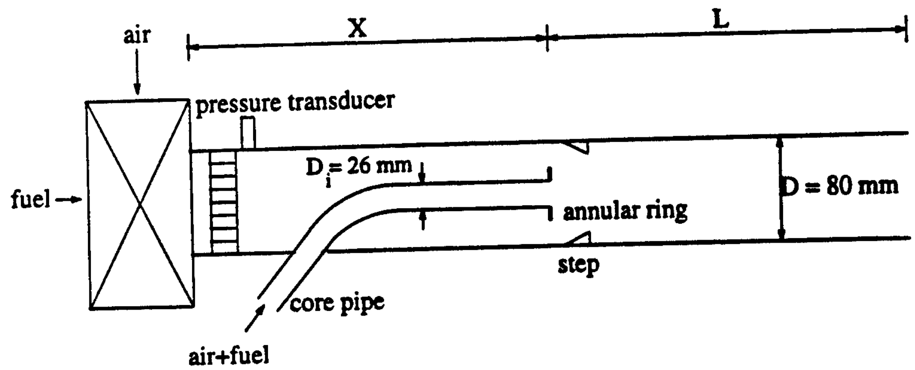

Figure 1: Annular Gas Turbine Combustor

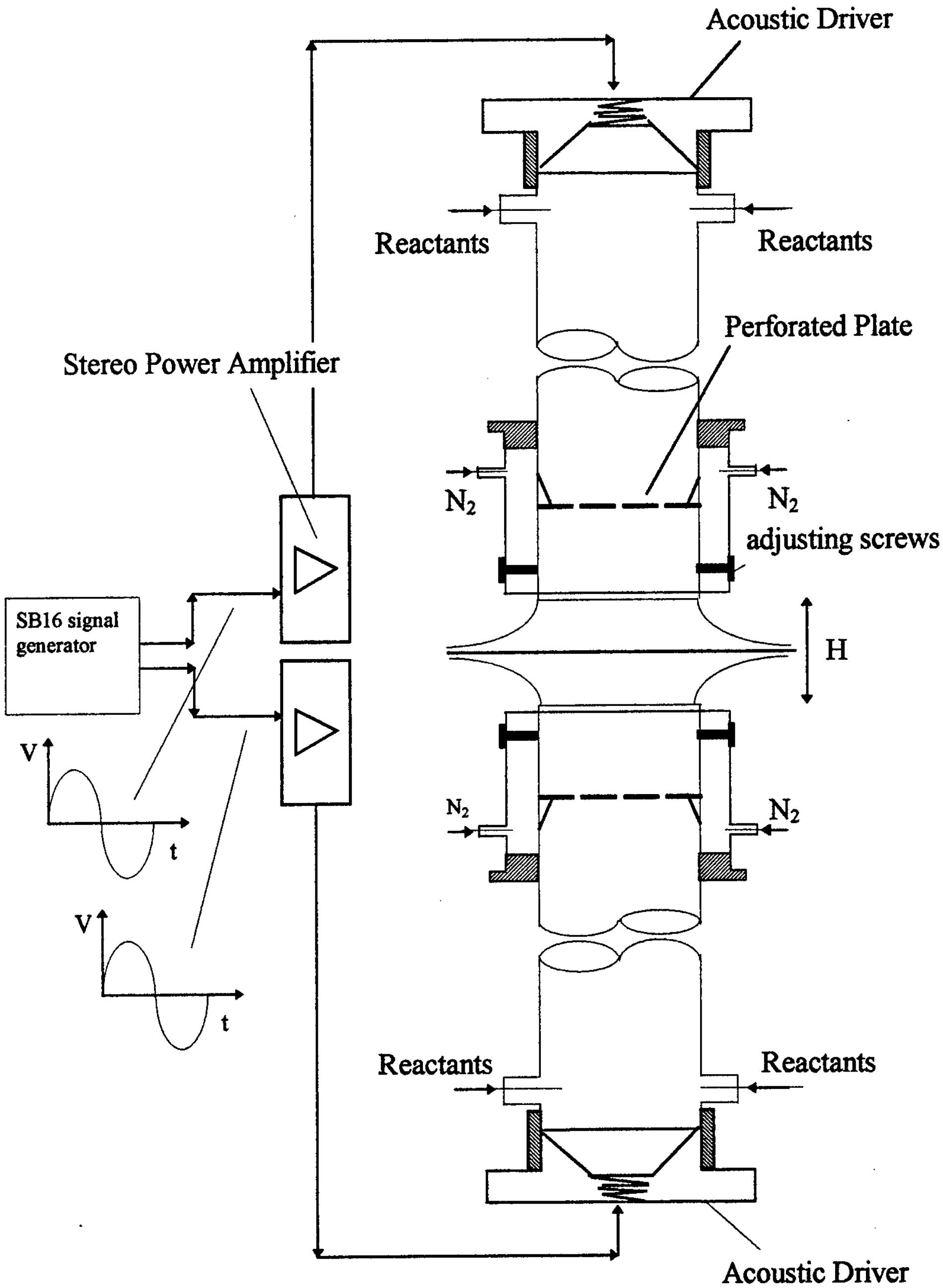

Figure 1 The flow configuration

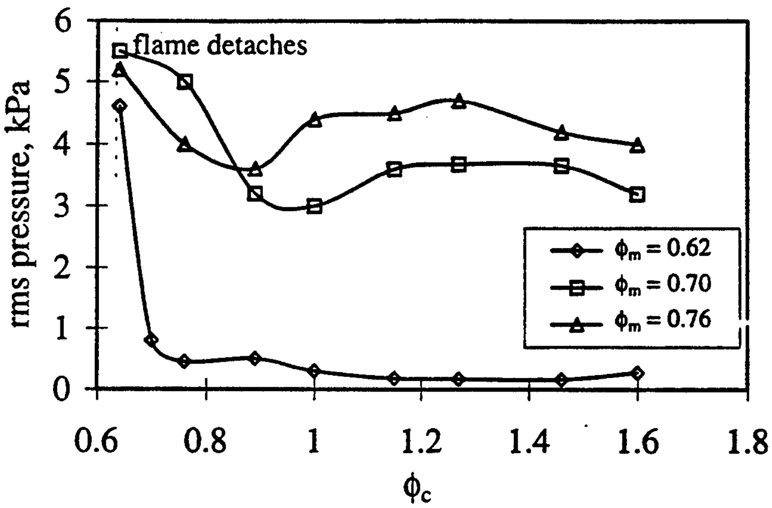

Figure 3: Influence of equivalence ratio on antinodal rms pressure fluctuation
area blockage ratio of annular ring = 0.29, area blockage ratio of step = 0.35
axial separation between annular ring and step = 40 mm

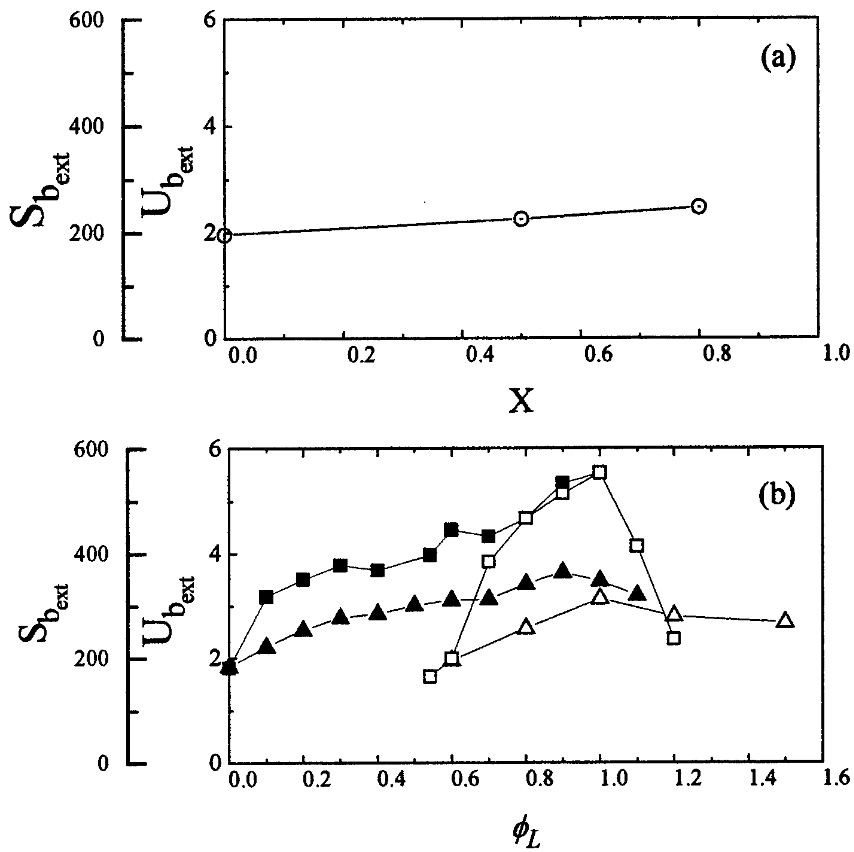

Figure 4 Extinction bulk velocities, $U_{b_{ext}}$ in m/s, and bulk strain rates, $S_{b_{ext}}$ in s^{-1}, of *unforced* counterflow flames; (a) diffusion and partially premixed flames; (b) □ twin symmetric; ■ twin asymmetric with the sum of equivalence ratios of the opposed streams equal to twice the stoicjiometric; Δ single premixed stabilised against air; ▲ single premixed stabilised against fuel. The x-axis is the air volume fraction in the fuel stream in graph (a) and the equivalence ratio of the lower stream in graph (b)

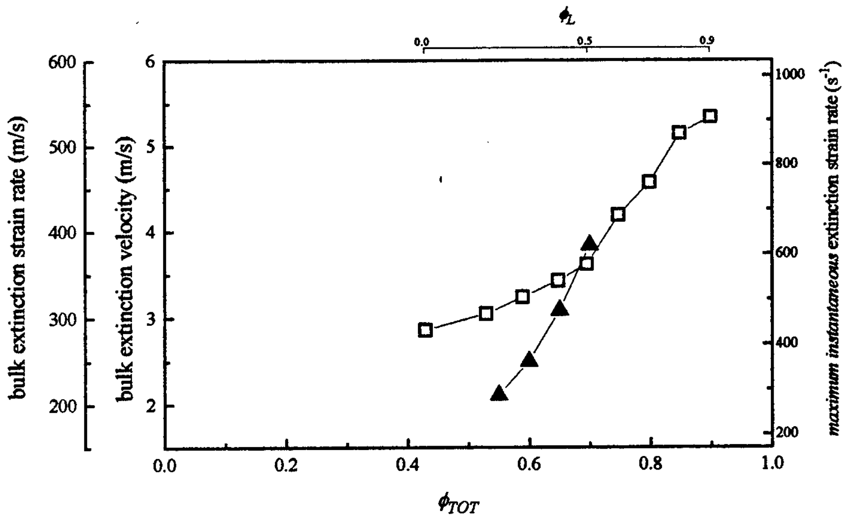

Figure 5 Extinction bulk velocities and bulk and mean strain rates of unforced lean premixed flames as a function of the total equivalence ratio, based on the fuel and air mixtures of both streams; □ asymmetric flames with 0.9 equivalence ratio of one stream; ▲ symmetric flames.

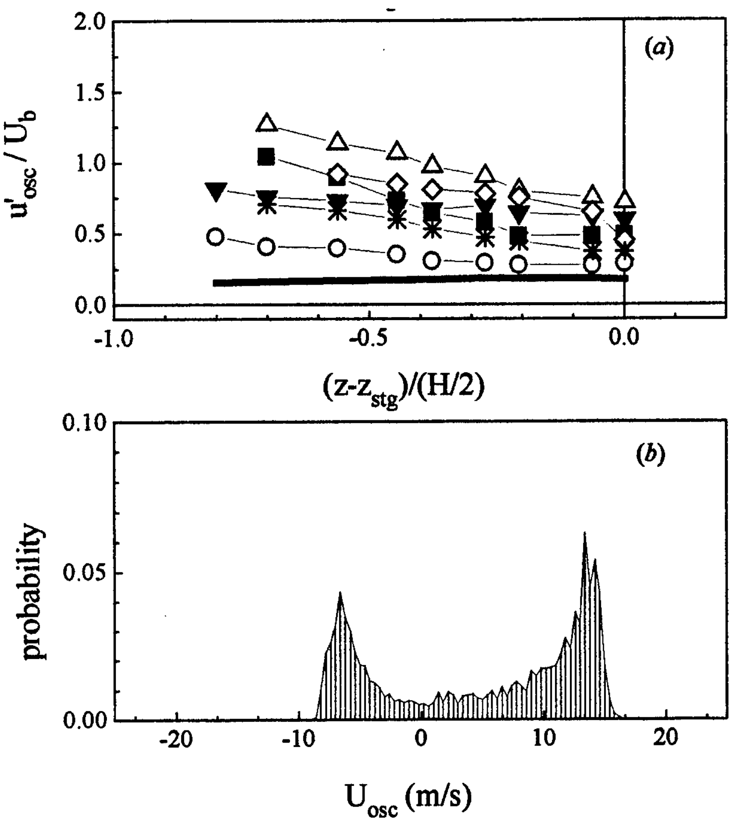

Figure 6 (a) Profiles of the rms of the axial velocity fluctuations along the 'lower' half of centreline as a function of normalised axial distance at different frequencies; ○ 100 Hz, ■ 200 Hz, Δ 400 Hz, ▼ 600 Hz, ◇ 800 Hz, ✳ 1000 Hz; line corresponds to measurements *without* oscillations; (b) typical probability distribution of axial velocity component during periodic forcing.

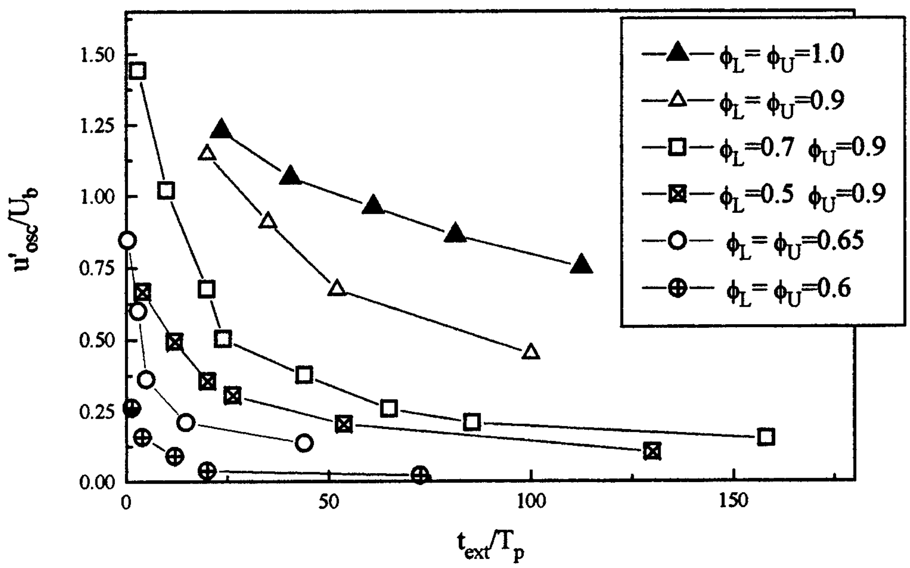

Figure 7 Extinction times of symmetric and asymmetric flames forced at 200 Hz, as a function of the amplitude of the imposed forcing.

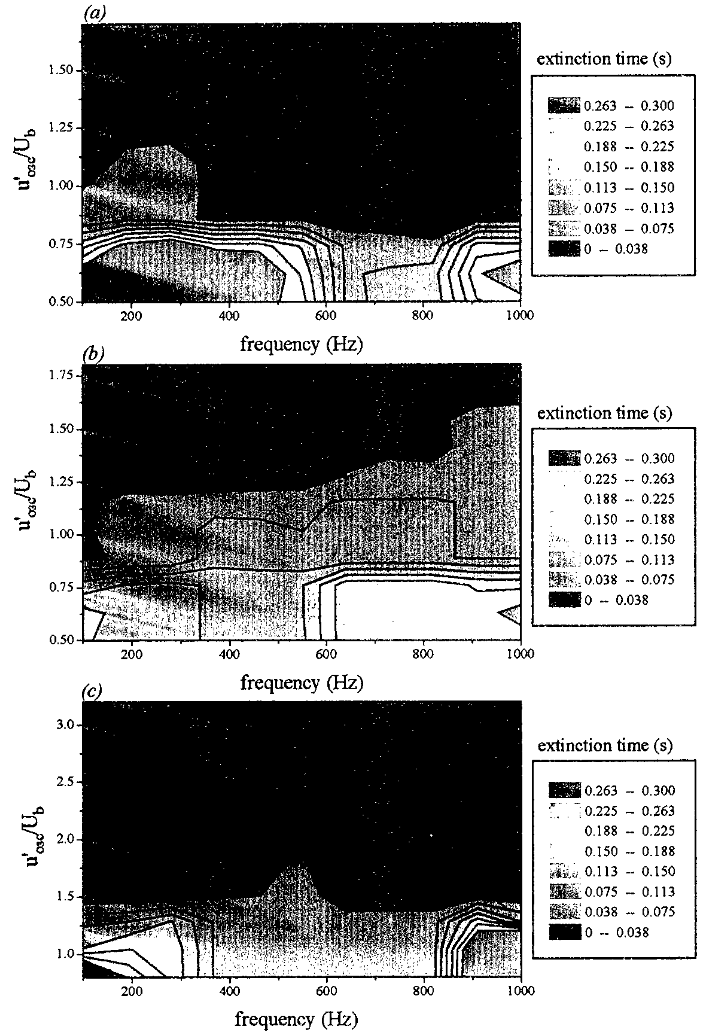

Figure 8 Extinction time as function of r.m.s. of axial velocity fluctuations and oscillation frequency, for *twin symmetric* premixed flames; (*a*) lean (φ_L=φ_U=0.7); (b) stoichiometric (φ_L=φ_U =1.0); *(c)* rich (φ_L=φ_U =1.1).

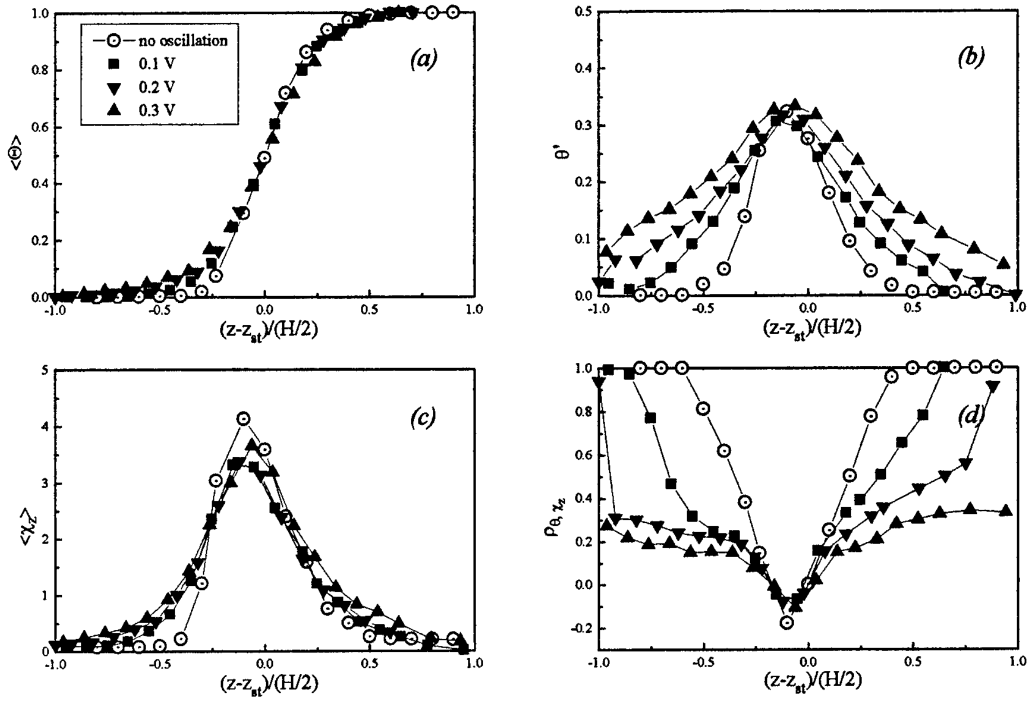

Figure 9 Mean scalar concentration (*a*), scalar fluctuations (*b*), mean axial scalar dissipation (*c*) and correlation coefficient (*d*) as a function of the input voltage to the speakers. The flow was forced at a frequency of 200 Hz

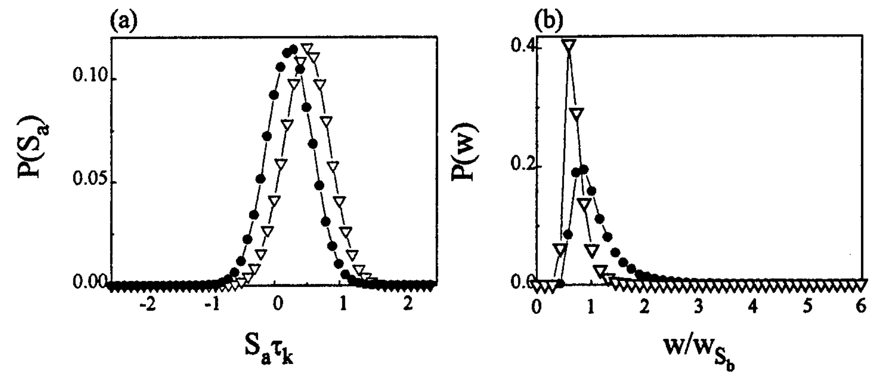

Figure 10 Probability distributions of the total strain, S_a, acting on the scalar interface, graph (a), and the resulting mixing layer width, w, graph (b); • total strain equal to the turbulent strain rate; ∇ total strain equal to the sum of the bulk and the turbulent strain rates. All probabilities are multiplied by 100, τ_k in graph (a) is the Kolmogorov microscale and w_{S_b} in graph (b) is the interface width when only the bulk strain is considered.

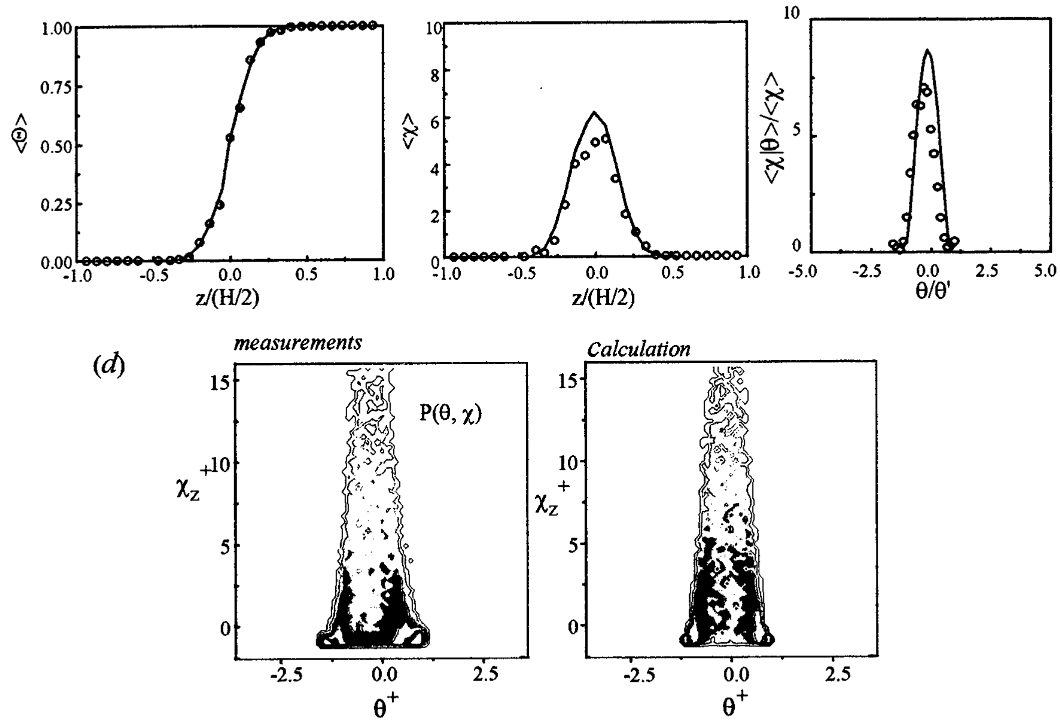

Figure 11 (*a*) Mean scalar concentration, $<\Theta>$, and (*b*) mean scalar dissipation, $<\chi>$, along the centreline of an unforced counterflow; (c) mean conditional scalar dissipation, $<\chi/\theta>$, at stagnation (*z/(H/2)* = 0); (d) joint probability distributions of the scalar fluctuations, θ, and the scalar dissipation χ at stagnation. In graphs (*a*), (*b*) and (*c*) *symbols* measurements (reference 2); *solid line* calculations.

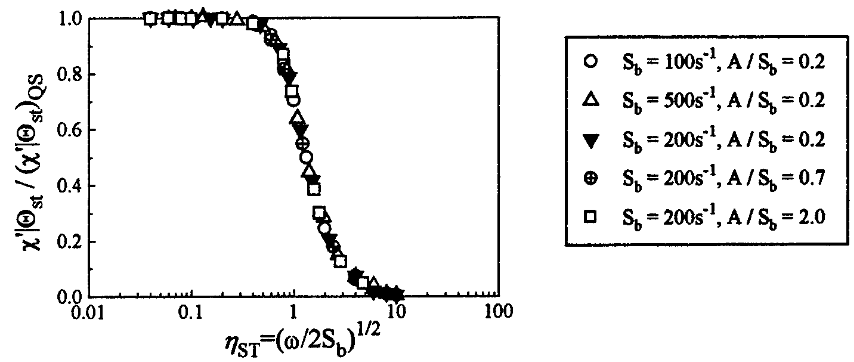

Figure 12 R.m.s. conditional scalar dissipation, $\chi'|\Theta_{st}$, normalised by its quasi-steady value, $(\chi'|\Theta_{st})_{QS}$, as a function of the ratio of the diffusion to the oscillation time scale.

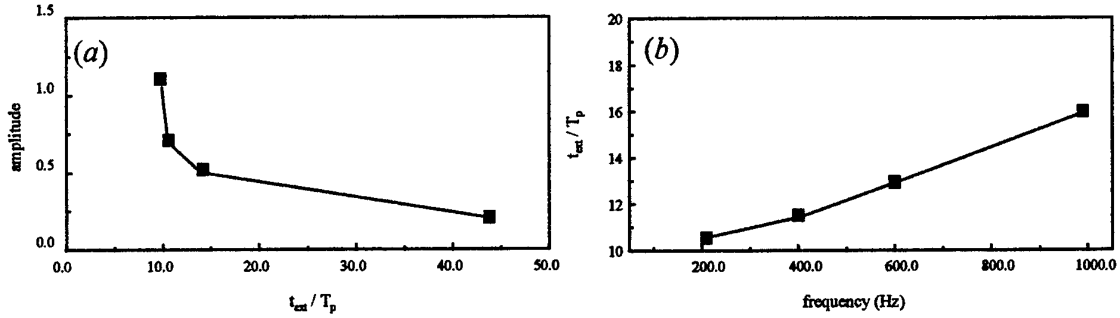

Figure 13 Calculated extinction timescales, t_{ext}, as a function of amplitude (*a*) and frequency (*b*) of the imposed oscillation. In both graphs extinction times are normalised with the oscillation period, T_p.

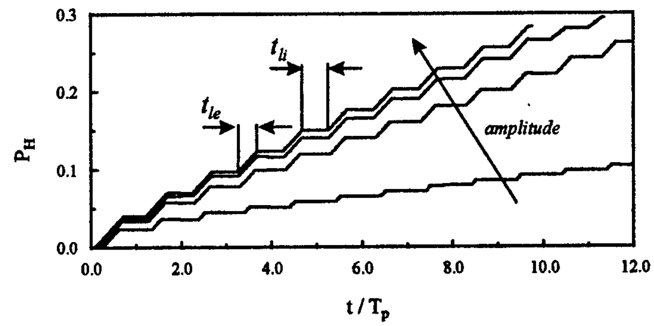

Figure 14 Cumulative probability of the values of the scalar dissipation that exceed a critical quenching limit during imposed forcing.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	01.05.98	Final report, period from 07.06.98

4. TITLE AND SUBTITLE

Combustion oscillation, extinction and control

5. FUNDING NUMBERS

--

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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8. PERFORMING ORGANIZATION REPORT NUMBER

TF/98/10

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

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London NW1 5TH

10. SPONSORING /MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

None

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Naturally occurring pressure oscillations in a model combustor were quantified with heat release around 100 kW as functions of geometric and flow parameters and actively controlled by the oscillation of fuel flow. Amplitudes up to 10 kaW were dominated by the quarter-wave frequency of the duct length upstream of an annual ring, depending on the equivalence ratio of the annular flow and decreased as ring and a step were moved closer. Active control of pressure oscillations was sensitive to the location and addition of oscillated fuel and was more effective with oscillations of fuel in the main flow.

Experiments with opposed flames showed that forced flame extinction depended on the total duration of pulsation and ranged from a few milliseconds to almost a second. Extinction times increased quasi-exponentially with decreasing amplitude and increasing frequency of oscillation for diffusion flames but were a non-monitonic function of the frequency inpremixed flames, with the longest extinction times corresponding to higher frequencies.

The characteristics of the opposed flames were represented by the concept of a mixinglet with the width of the mixing layer a function of the sum of the bulk, the turbulent the periodic strain and the mixinglet assumed to be randomly convected. The results reproduced measured trends in the mean an rms of the scalar fluctuations and the dissipation in non-combusting, periodically forced, opposed jet flows and include extinction times in opposed flames that increased exponentially with frequency and decreasing amplitude, again in accord with experiment.

14. SUBJECT ITEMS

Combustion oscillations; extinction and re-light; opposed flames; model gas turbine combustor; active control.

15. NUMBER OF PAGES

29 incl. figs

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

ATTACHMENT 1 PAGE 1